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Millimeter-Wave and Sub-THz Modulated Metasurface Antennas

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Abstract – Modulated metasurfaces (MTSs) have sprung up in the last decade as an attractive solution for wave guidance and radiation. More precisely, modulated MTS antennas stand out for providing an unprecedented control of the aperture fields with low-profile and lightweight structures. In this class of antennas, a surface-wave (SW) is gradually radiated, owing to its interaction with a modulated impedance boundary condition (IBC). This IBC is typically implemented in the microwave regime by several thousands of sub-wavelength patches printed on a grounded slab. However, dielectric losses may hinder the use of standard printed circuit board (PCB) technology at higher frequencies. In this paper, we will address this issue by introducing a new class of metal-only modulated MTS, which can be easily fabricated by additive manufacturing or micro-machining for millimeter-wave and sub-THz applications.

I. INTRODUCTION

Modulated metasurfaces (MTSs) can be efficiently used to guide the propagation of surface-wave (SW) wavefronts [1] or to gradually radiate the power carried by a SW [2]. Formally, the MTS aperture can be represented by a space-varying anisotropic impedance boundary condition (IBC). The IBC modulation in MTS antennas is typically periodic and, by properly choosing the period of this modulation, the -1 mode in the Floquet expansion can enter the visible region and provide the desired radiation effect. Besides polarized and shaped beams [2], this class of antenna can provide multiple-beams [3] and broadband operation [4].

In the microwave regime, modulated MTS antennas typically consist of several thousands of sub-wavelength patches printed on a grounded slab and fabricated by standard PCB technology. However, dielectric losses may significantly reduce their radiation efficiency for millimeter-wave and sub-THz applications. Although one could use either polymers (e.g. benzocyclobutene or cyclic olefin copolymer) or high-resistivity silicon as high-performance substrates, metal-only solutions constitute an extremely promising alternative. Indeed, metal-only designs will be less susceptible to thermal variation and will not suffer for dielectric property change due to a high level of radiation [5]. Such properties are advantageous, for instance, to withstand harsh environments in space exploration.

This paper presents a class of modulated MTS antennas that can be fabricated entirely in metal, and it is organized as follows. First, we will succinctly describe the design process and present the unit-cell that enables the metallic implementation of the IBC. Then, two different fabrication techniques are discussed, along with their advantages and limitations. Finally, conclusions are drawn.

II. METAL-ONLY MODULATED MTS ANTENNAS

In the remainder of this paper we will consider, without loss of generality, circular apertures and a cylindrical reference system with unit vectors $(\hat{\rho}, \hat{\phi})$. In a nutshell, the design problem consists in finding an impenetrable IBC $\underline{\underline{X}}(\rho)$ that provides the desired aperture fields \mathbf{E}_A . This IBC relates the tangential fields on the MTS aperture as

$$\mathbf{E}_t|_{z=0^+} = \underline{\underline{X}}(\rho) \cdot \hat{\mathbf{z}} \times \mathbf{H}_t|_{z=0^+} \quad (1)$$

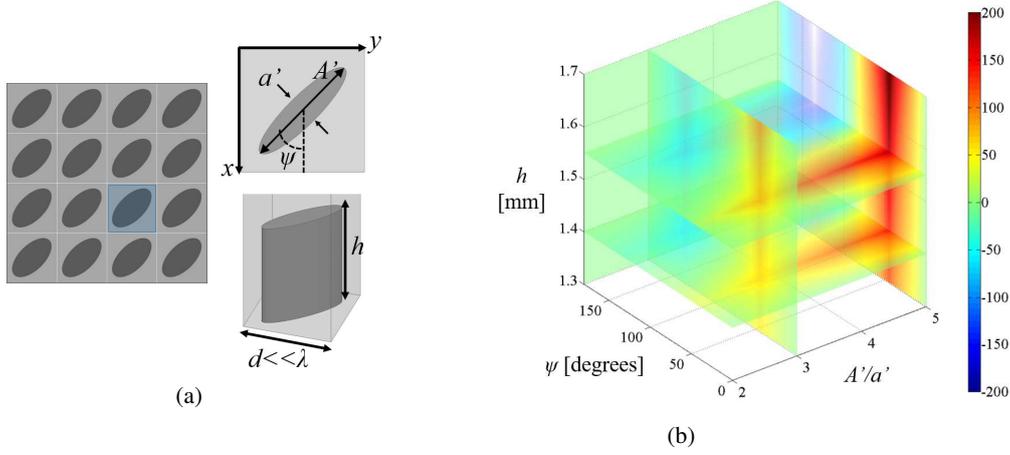


Fig. 1: (a) Description of the unit-cell geometry and local periodicity assumption. (b) Example of database relating the geometry of the unit-cell with the corresponding reactance tensor.

where $\mathbf{E}_t|_{z=0^+}$ and $\mathbf{H}_t|_{z=0^+}$ are the total tangential electric and magnetic fields, respectively. Following the procedure described in [6], one can calculate $\underline{\underline{\mathbf{X}}}(\rho)$ as

$$\underline{\underline{\mathbf{X}}}(\rho) \cdot \begin{Bmatrix} \hat{\rho} \\ \hat{\phi} \end{Bmatrix} = \left[\mathbf{X}_0 \begin{Bmatrix} \hat{\rho} \\ \hat{\phi} \end{Bmatrix} \pm 2\text{Im} \left(\frac{\mathbf{E}_A}{I_{TM} H_1^{(2)}(\beta_{sw}\rho)} \right) \right] \mathbf{U}_A \quad (2)$$

where I_{TM} is the SW complex excitation coefficient, $H_1^{(2)}(\cdot)$ is the Hankel function of the second kind and first order and β_{sw} is the SW wave-number, related to the ρ component of $\underline{\underline{\mathbf{X}}}$ as $\beta_{sw} = k\sqrt{1 + (X_0/\zeta)^2}$.

Once the value of $\underline{\underline{\mathbf{X}}}(\rho)$ on the aperture is known, one has to find metallic elements that reproduce the local behavior of the IBC tensor. Here, we explore the use of cylinders with elliptical cross-section (see Fig.1a), as in [7, 6, 8]. To obtain the antenna layout, we first build a database that links the geometry of the cylinders with a reactance tensor. Fig.1b shows the variation of $X_{\rho\rho}$ with the different geometrical features. Since the variation between one element and its neighbors is small (see Fig.1a), we can assume that the structure is locally periodic and use a periodic solver to build our database. Next, $\underline{\underline{\mathbf{X}}}(\rho)$ is sampled on a Cartesian lattice, with unit-cell size equal to d . Finally, each sample is implemented using a metallic pillar with the geometry retrieved from the database.

The peak gain and relative bandwidth (defined as $\Delta f/f_0$, with Δf being the total bandwidth and f_0 the central frequency) of these antennas are closely related. Practical values of $\Delta f/f_0$ may vary between 3% and 9% when the antenna gain goes from 40 to 28.5 dB. Nonetheless, one can trade gain for larger bandwidths as explained in [4]. Another crucial aspect consists in choosing the most appropriate fabrication technique at each frequency band. The fabrication technique may impose some restrictions in the design phase, for instance, the maximum ratio between cylinder height and unit-cell side. In general, the technological choice is mostly dictated by the dimensions of the MTS unit-cells.

A. Additive manufacturing

In the millimeter-wave range, we have demonstrated that metal additive manufacturing (AM) can be used to realize structures at Ka band [6]. Fig.2a shows a MTS antenna where the elliptical cylinders have been grown by laser beam melting (LBM) on an aluminum base-plate using AlSi10Mg powder. The feeding circuit (not shown here) was machined on the other side of the base-plate.

B. Micro-machining

At higher frequencies, the maximum accuracy and surface roughness provided by LBM and similar methods lead to strong limitations in the antenna performance. However, it is possible to use micro-machining as a high precision fabrication technique. In this regard, one of the most popular approaches is to use plasma etching, such as deep reactive ion etching (DRIE). This way, one can manufacture the MTS texture with an excellent accuracy

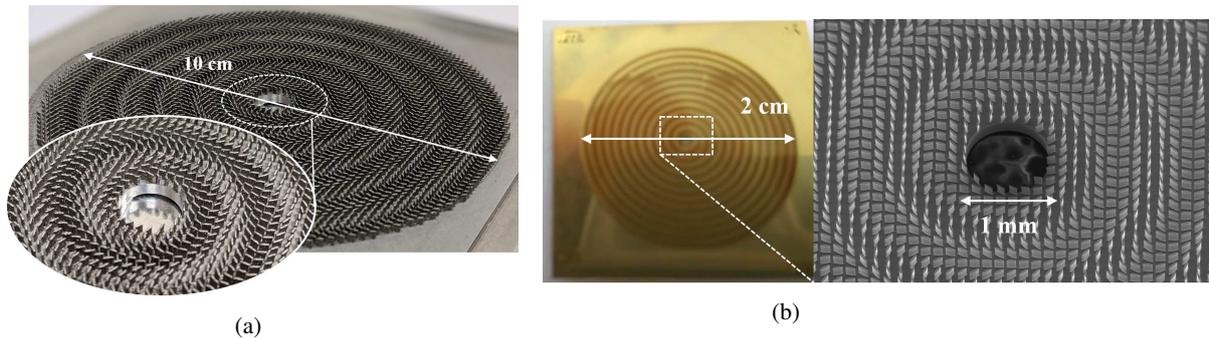


Fig. 2: (a) Ka-band modulated MTS antenna fabricated by metal additive manufacturing. (b) Modulated MTS antenna operating at 300 GHz and fabricated by DRIE.

by etching a Silicon wafer that is afterward metalized by sputtering [7, 8]. The main drawback of DRIE is that the maximum etching depth cannot be larger than a few hundreds of microns, so it is difficult to apply it at lower frequencies. Fig.2b shows one of our 300 GHz prototypes fabricated by DRIE.

III. CONCLUSION

This paper has discussed a metal-only modulated MTS antenna along with two possible fabrication techniques, one for millimeter-waves and the other one in the sub-THz range. The proposed structure allows one to overcome some of the limitations imposed by the use of dielectric substrates at high frequencies and/or in some applications. At the conference, we will present new designs and further discuss important aspects like the tapering of the aperture fields to increase the aperture efficiency or the use of new modulations to enlarge the bandwidth.

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